Preprint
UCRL-JC-143363

Analysis of Forcing Response, and Feedbacks In A Paleoclimate Modeling Experiment

K. E. Taylor, C. D. Hewitt, P. Braconnot, A. J. Broccoli, C. Doutriaux, J. F. B. Mitchell

This article was submitted to
3rd Paleomodeling Intercomparison Project Workshop, Montreal, Canada, October 4-8, 1999

U.S. Department of Energy

Lawrence
Livermore
National
Laboratory

April 11, 2001

ANALYSIS OF FORCING, RESPONSE, AND FEEDBACKS IN A PALEOCLIMATE MODELING EXPERIMENT

K.E. Taylor[1], C.D. Hewitt[2], P. Braconnot[3], A.J. Broccoli[4], C. Doutriaux[1], J.F.B. Mitchell[2], and PMIP Participating Groups

[1] Program for Climate Model Diagnosis and Intercomparison (PCMDI), LLNL, Livermore, California, USA (taylor13@llnl.gov)
[2] Hadley Centre, UKMO, Bracknell, England, UK
[3] Laboratoire des Sciences du Climat et de l'Environnement, CEA, Saclay, France
[4] Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

INTRODUCTION

It is often argued that paleoclimate studies are necessary to determine whether climate models and their predictions of future climate change can be trusted. An overall measure of the sensitivity of global mean surface temperature to a given radiative perturbation is provided by the global climate sensitivity parameter. In climate model experiments, this parameter appears to be moderately independent of the cause of the perturbation [see, for example, Hansen et al. (1997) and Hewitt and Mitchell (1997)], but it may differ from one model to the next by as much as a factor of three (IPCC, 1995). Moreover, there are some scientists who claim that all models are much more sensitive than the climate system itself (Lindzen, 1997). Thus it would be valuable to determine which models (if any) are consistent with the paleoclimate record and what factors are responsible for model differences in sensitivity.

In an analysis of the Paleoclimate Modeling Intercomparison Project (PMIP) simulations of the Last Glacial Maximum (LGM) of 21,000 years ago, we have calculated how the "forcing" and feedbacks determine the climatic response. In the PMIP context, the ice sheet distribution is prescribed and the resulting increase in planetary albedo is the most important "forcing" factor. Also important are radiation perturbations induced by changes in atmospheric CO_2 concentration. Here we describe a new, approximate method for estimating the strength of forcing and feedback factors from commonly archived model output. We also summarize preliminary results from the PMIP experiment, which show that differences in forcing and to a lesser extent differences in feedbacks can explain differences in surface temperature response.

ANALYSIS

In the PMIP LGM experiments a common ice sheet reconstruction was imposed on all models. The same fractional change in carbon dioxide concentration was prescribed, and the orbital parameters were identical for all models. In a subset of PMIP models the resulting climate change was computed using fixed-depth mixed layer models. Figure 1 shows the change in global mean surface temperature for the PMIP models with computed SST's.

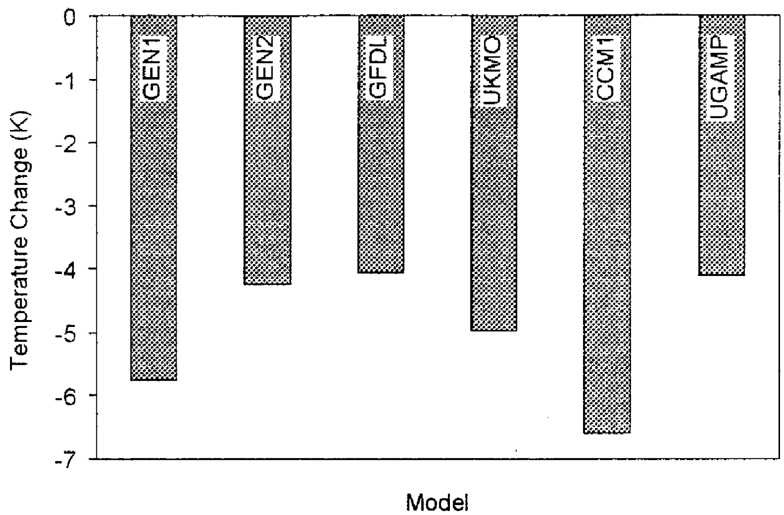

Figure 1 – Change in global mean surface temperature change between the present and the LGM as simulated by six PMIP models with computed SST's.

Model estimates of changes in global mean temperature vary from about –4 K to –6.5 K. The question addressed here is how much of the difference in temperature response between models is due to differences in radiative forcing and how much is due to differences in feedbacks. We shall now describe a new method of estimating shortwave forcing as well as feedbacks that affect shortwave fluxes.

In the context of climate change experiments, radiative forcing is defined as the net change in the radiative fluxes near the top of the atmosphere (TOA) resulting from some imposed, prescribed change in "boundary conditions" (e.g., a change in surface albedo or a change in atmospheric CO_2 concentration). The traditional way of computing radiative forcing requires modifications to the model code that are not trivial. In addition, the calculation adds a computational burden to the experiment that for some models is quite significant. Consequently, for the PMIP experiments most groups did not calculate the radiative forcing.

The strength of various feedbacks in climate change experiments normally requires several additional simulations in which different feedbacks are suppressed, and again this can obviously greatly increase the computational expense. Important feedbacks that can be important include water vapor feedback, cloud feedback (including changes in cloud fraction, the distribution of clouds, and cloud optical properties), and surface albedo feedbacks, for example, due to changes in sea ice and snow cover. Again PMIP modeling groups have not performed these additional simulations.

Without at least some estimate of the forcing and feedbacks it is difficult to understand why models respond differently to the same changes in imposed boundary conditions. We have therefore developed an approximate way of calculating these quantities from the monthly mean output available from most of the PMIP models. The method is applicable primarily to shortwave forcing and feedback, but some estimate of longwave cloud feedback is also possible.

In order to estimate the strength of various components of shortwave forcing and feedback, we rely on a shortwave radiation model shown schematically in figure 2.

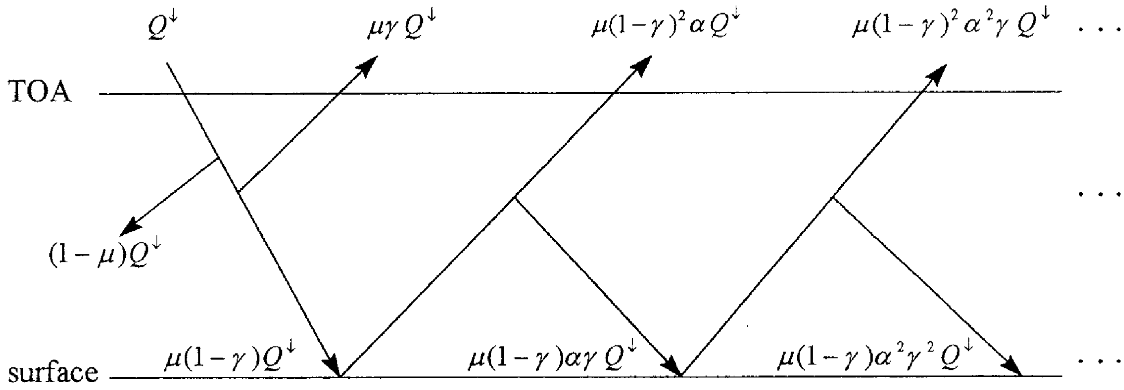

Figure 2 – Schematic representation of simple shortwave radiation model showing fluxes passing through the atmosphere and being partially reflected on each pass, where $Q^{\downarrow}$ is the insolation, α surface albedo, and γ and μ are the atmospheric scattering coefficient and transmissivity, respectively.

The column model includes a single atmospheric layer that scatters radiation passing downward or upward through it, but absorbs radiation only on the first pass (after which the radiant energy in the spectral bands where significant absorption occurs is assumed to be substantially depleted). In order to approximate the shortwave radiative properties of each PMIP model, the parameters, α, γ and μ, are chosen to reproduce each model's simulated surface and top of the atmosphere fluxes. The parameter values vary with model, with grid cell, and with month of the year. Different parameters apply for the overcast and clear-sky portions of each grid cell.

With this simple model, it is possible to estimate the shortwave forcing due to changes in surface albedo or insolation changes. In the LGM PMIP experiment a large change in glacial extent is prescribed, which implies large changes in surface albedo. The change in surface albedo is calculated from the surface upward and downward streams of shortwave radiation, which are routinely archived as part of a model's output. The effect of these changes on the top of the atmosphere fluxes can be estimated using the simple model described above. To test whether the model yields an accurate approximation to the true radiative forcing, two modeling groups (from

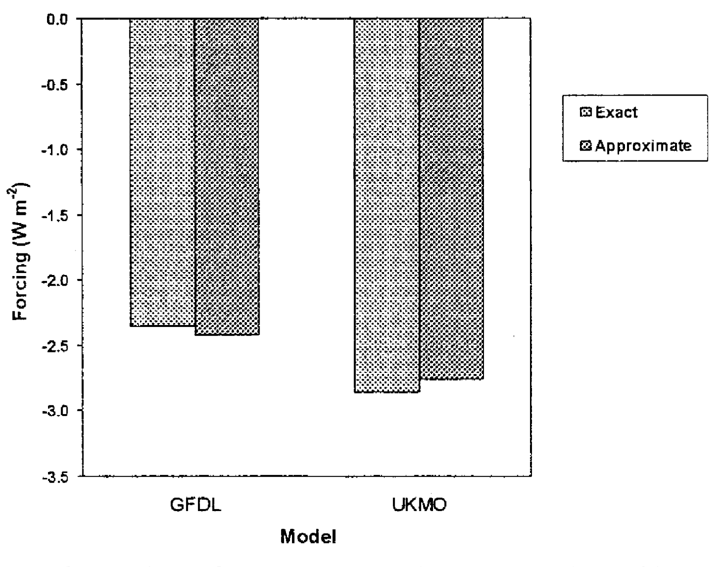

Figure 3 – Comparison of exact and approximate calculations of ice-sheet shortwave radiative forcing in two PMIP models.

the Hadley Centre and the Geophysical Fluid Dynamics Laboratory) calculated the forcing using the traditional so-called "exact" method. A comparison of the exact method with the approximate method used here is shown in figure 3.

Figure 3 shows that in both models the approximate calculation is quite accurate and much smaller than the differences between the models. Thus, it will be useful to apply the same method to the other PMIP models where the exact calculation is unavailable. The results from most of the PMIP models that performed an LGM simulation are shown in figure 4.

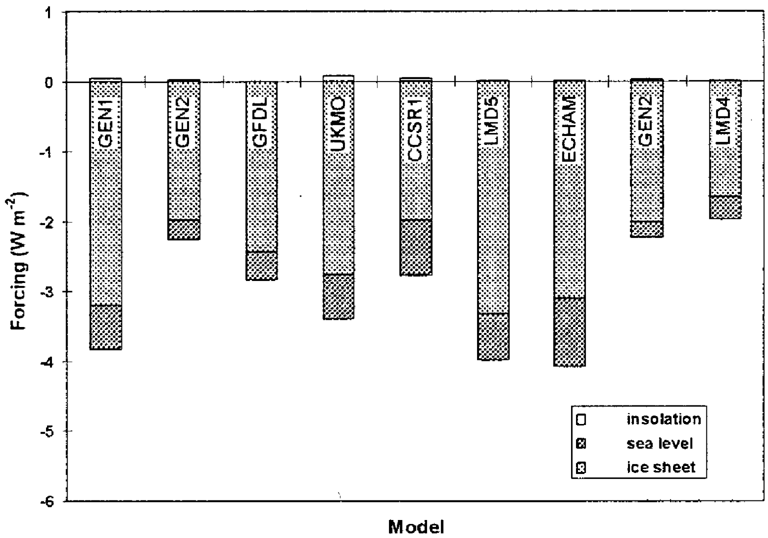

Figure 4 – PMIP model estimates of shortwave radiative forcing for the LGM resolved into components due to changes in insolation (caused by changes in Earth's orbit) and changes in surface albedo due to increases in glacial ice, and due to lowering of sea level (which exposes land that is more reflective on average than ocean). The above figure includes models with prescribed SST's, but not all PMIP models archived the needed model output, so some models are not represented in the figure. The figure shows that forcing due to changes in the insolation pattern is negligible for the LGM experiment.

There is about a factor of two difference in the shortwave radiative forcing estimated by the models. The forcing due to differences in the insolation pattern are negligible compared to the changes in surface albedo. In addition to the forcing components shown in figure 4, there is a forcing due to the lower concentration of carbon dioxide during the LGM. All the models reduced the CO_2 concentration by the same fraction. We shall assume here that the forcing calculated by both the UKMO model and the GFDL model (-1.7 W/m^{-2}) applies for all models. This assumption is not strictly valid since Cess et al. (1993) show that there is some variation in forcing in CO_2 doubling experiments, but if a similar range applies to PMIP models, the uncertainty in this number is less than ± 0.2 W/m^{-2}. Thus the model differences in CO_2 radiative forcing should be very much smaller than the shortwave radiative forcing differences apparent in figure 4.

The first four models shown in figure 4 computed sea surface temperature (SST), while the others prescribed SST according to the CLIMAP reconstruction. For the models with computed SST's, we plot in figure 5 the global mean temperature change versus the forcing.

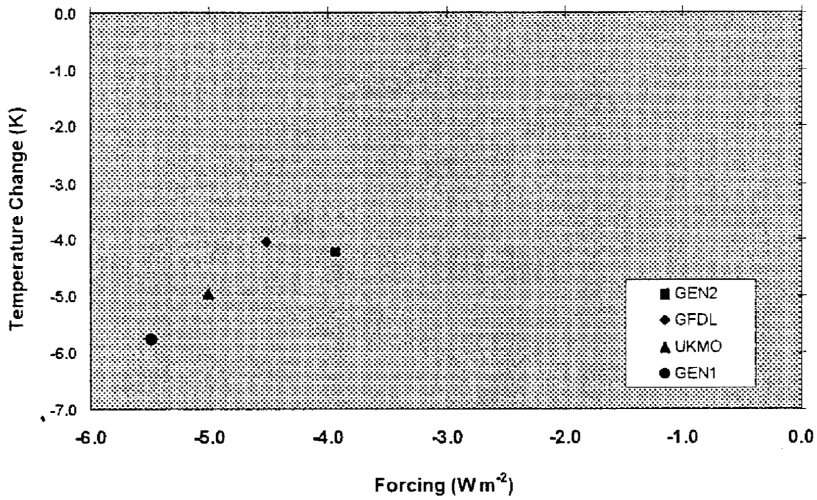

Figure 5 – Forcing and response for 4 PMIP models with computed SST's.

If all four models had the same global climate sensitivity, the plotted points would all fall along a line passing through the origin. The scatter about such a line indicates that even accounting for differences in forcing, the models show differences in sensitivity that must be due to differences in climate feedbacks. It is possible to evaluate the strengths of different shortwave feedbacks using the same model described above. It is not easy to evaluate the longwave feedbacks, but a measure of the total longwave feedback can be calculated as a residual by subtracting from the change in outgoing longwave radiation at the top of the atmosphere (TOA) the longwave radiative forcing and a term referred to here as the direct linear "response." The response, R, is defined such that the fractional change in the TOA longwave flux equals the fractional change in longwave emitted by the surface:

$$R = \frac{F_{\mathrm{TOA}}}{F_s} \Delta F_s$$

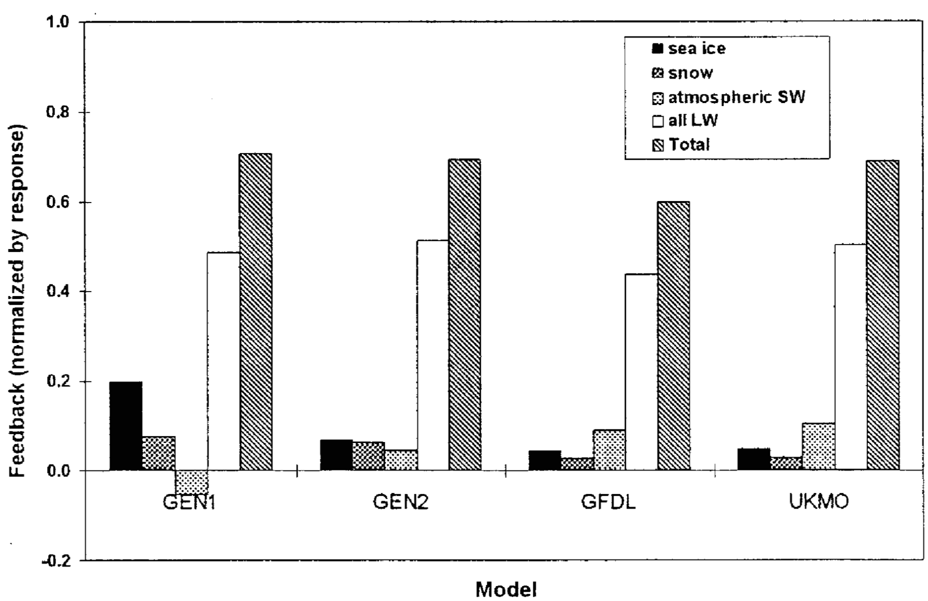

Figure 6 – Strength of feedbacks in four PMIP models, normalized by response, R.

Figure 6 shows the strengths of the various feedbacks for four of the PMIP models. We see that the total feedback differs from one model to the next and that there are considerable differences in the individual feedbacks. The longwave feedback is due primarily to water vapor and cloud changes. The atmospheric shortwave feedback is primarily due to cloud changes. Note that the GFDL model has a weaker longwave feedback than the others, which is largely responsible for its weaker climate sensitivity shown in figure 5. The Genesis 1 model has stronger sea ice and snow feedbacks, which are partially offset by a negative shortwave cloud feedback.

CONCLUDING DISCUSSION

We have found that although the same boundary condition changes were imposed in all the PMIP models, the shortwave forcing (accounting for more than half the total forcing) varied by a factor of two among the models. Based on a previous study (Cess et al., 1993) the longwave forcing differences are relatively small, so the PMIP models estimatea LGM forcing in the range of –4 to –6 W/m^{-2}. A substantial fraction of the difference in the global mean temperature response can be explained in terms of these differences in forcing, but there are also differences in total feedback that are important. In fact individual shortwave feedbacks involving clouds are not even of the same sign in all models.

Despite the differences in feedbacks, the four PMIP models analyzed in detail here indicate that for forcing similar to that of the last glacial maximum, the climate sensitivity is about $1\ K\ W^{-1}\ m^2$ with a range of $\pm 10\%$. This would imply a global warming in response to a doubling of CO_2 in the range of about 3.1 to 3.7 K.

ACKNOWLEDGEMENTS

This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

REFERENCES

Cess R.D., M.-H. Zhang, G.L. Potter, *et al.*, 1993: Uncertainties in carbon dioxide radiative forcing in atmospheric general circulation models. *Science*, **262**, 1252-1255.

Hansen, J.E., M. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res.*, 6831-6864.

Hewitt, C.D., and J.F.B. Mitchell, 1997: Radiative forcing and response of a GCM to ice age boundary conditions: cloud feedback and climate sensitivity. *Clim. Dyn.*, **13**, 821-834.

IPCC Climate Change 1995, J.T. Houghton, ed., Cambridge University Press (1996).

Lindzen, R.S., 1997: Can increasing carbon dioxide cause climate change? *Proc. Natl. Acad. Sci., USA*, **94**, 8335-8342.